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Synthesis and Variable Temperature Electrical Conductivity Studies of Highly Ordered TiO₂ Nanotubes

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ABSTRACT

Rafts of aligned, high aspect ratio TiO₂ nanotubes were fabricated by an electrochemical anodization method and their axial electrical conductivities were determined over the temperature range 225-400 °C. Length, outer diameter and wall thickness of the nanotubes were approximately 60-80 μm, 160 nm and 30 nm, respectively. Transmission electron microscopy studies confirmed that the TiO₂ nanotubes were initially amorphous, and became polycrystalline anatase after heat treatment at temperatures as low as 250 °C in air. The activation energy for conductivity over the temperature range 250 - 350 °C was found to be 0.87 eV. The conductivity values are comparable to those of nanocrystalline and nanoporous anatase thin films reported in literature.

Keywords: Electrochemical anodization of Ti, TiO₂ nanotubes, and electrical conductivity.

1. INTRODUCTION

Titania is of tremendous interest for applications in photovoltaic devices such as solar cells^{1,2}, photo-catalysis^{3,4} and photo-electrochemistry⁵. For example, titania is a key component of the dye-sensitized solar cell (DSSC). TiO_2 is used to transport electrons from the light absorbing layer (such as $\text{Ru}(\text{dcbpy})_2(\text{NCS})_2$ dye) to the current collector. Recently, there has been tremendous interest in the use of nanocrystalline titania and mesoporous networks of titania in both DSSCs utilizing liquid electrolytes as well as solid-state solar cells^{6,7,8}. Mesoporous titania networks are extensively used to investigate performance of solar cells, particularly the Grätzel cell² designs, and several approaches have been developed to fabricate nanostructured titania⁶. Nanotubes of titania have also attracted attention owing to their potential for application in photovoltaic devices⁹.

In several of these technological applications, understanding the temperature dependent conductivity is critical for understanding device performance, as well as to extract fundamental information on conduction mechanisms and activation energy for carrier transport.¹⁰ To the best of our knowledge, this paper presents the first electrical conductivity measurements of titania nanotubes.

2. EXPERIMENTAL

The fabrication procedure followed closely the method of Grimes and coworkers^{10,12}. A 2 cm x 1.5 cm titanium foil (99.7%; Sigma-Aldrich) with a thickness of 250 μm was immersed into an etching solution containing 0.334 g of NH_4F (Sigma-Aldrich) dissolved into 2.2 ml of DI water and 97.47 ml of ethylene glycol (anhydrous, 99.8%; Sigma-Aldrich). The solution was mixed for about 15 minutes using a magnetic stirrer bar before the commencement of anodization. The Ti foil was then connected to a working electrode. A Pt counter electrode with the same lateral dimensions and a thickness of 200 μm was also immersed into the same solution facing the working electrode. The reference electrode was connected to the potentiostat. The distance between Ti foil and Pt foil was 3.8 cm and applied voltage ranged from 55 to 75 DC V.

After the anodization was complete, the TiO_2 nanotubes, which comprised yellow flakes on both sides of the Ti foil, were washed with isopropyl alcohol and then immersed in a diluted HCl (0.1 M) solution for 1 hr. to remove any unwanted deposits and surface impurities

introduced during the anodization. Finally, the TiO₂ nanotubes were washed again with DI water and dried in an oven at 100 °C for a few hours.

Measurements of electrical conductivity through the film (i.e. along the axial direction of the nanotubes) were performed on pieces of flakes measuring about 1 mm x 1 mm. Devices were fabricated using silver electrodes on both sides and a stainless steel support plate. Electrodes were attached using pure silver enamel followed by a heat treatment at 70 °C. The stainless steel plate bearing the device was then mounted on a custom designed microprobe electrochemical system. Electrical conductivity measurements were performed in the frequency range of 300 KHz - 0.1 Hz using a sinusoidal voltage signal. Conductivity was estimated as conductance divided by electrode area, ignoring the hollowness of the tubes.

3. RESULTS AND DISCUSSION

In Figure 1 we present field emission scanning electron microscope (FESEM) images of TiO₂ nanotubes formed on the Ti metal surface. The TiO₂ nanotubes are approximately 60 µm long with 160 nm outer diameter and 30 nm wall thickness. It has been reported that increasing ammonium fluoride concentration, anodization potential and time result in longer nanotubes^{10,12}. However, we found that an anodization potential greater than 75 V caused dissolution of the surface of the Ti foil instead of the growth of titania nanotubes.

The mechanism of TiO₂ nanotubes formation in the NH₄F solution has been discussed by Mor et al¹². Oxide growth occurs due to the interaction of Ti with O²⁻ and hydroxyl ions and subsequent migration occurs due to an electric field gradient. Localized dissolution of the oxide due to the F⁻ ions similar to a corrosion process leads to pitting followed by pore growth. The tube formation occurs due to a geometric electric field intensity enhancement inside the pore region leading to vertical tube growth. Mor *et al.* have summarized the factors leading to tube array formation by considering the competition between electrochemical etching versus chemical dissolution in a recent review.¹¹ The tubes self-organize into a hexagonal array during growth. Indeed we observed a hexagonal array of pits left on the surface of the Ti foil after the growth and removal of the flake of TiO₂ nanotubes.

Transmission Electron Microscopy (TEM) studies showed that our TiO₂ nanotubes were originally amorphous. After they had been heated to 225 °C in air, held at these conditions for temperature stabilization and electrical conductivity measurements (~ 1hr), and cooled to

ambient temperature, they were observed to be partly crystalline by TEM. Samples heated to 250 °C in air, held at these conditions for temperature stabilization and electrical conductivity measurements, and cooled to ambient temperature appeared to be fully polycrystalline. Heating and cooling rates of the heat treatment were 1 °C/min. In Figure 2 we present TEM images of an as-prepared nanotube and of a 250 °C annealed nanotube. The corresponding TEM diffraction patterns indicate amorphous and polycrystalline anatase, respectively. The first eight rings of the crystalline diffraction pattern, in order of increasing diameter, correspond to the 101, 004, 200, 105+211, 204, 220+116, 215, and 224 reflections of anatase.

The impedance plot recorded at different temperatures is shown as an inset in Figure 3 in the form of a Nyquist plot. The high frequency part of the spectrum shows a semicircular arc as expected for an RC circuit. The lower frequency part is slightly extended. Polycrystalline titania samples usually show distinct or overlapping semicircular arcs corresponding to bulk and grain boundary responses. The as-prepared nanotubes are amorphous and are free from grain boundaries. However, the microstructures clearly show inter-tube boundary regions and such regions may contribute to distortions in low frequency part of the impedance plot. The conductivity is obtained from the intercept of the impedance curve with the x-axis, taking into account the sample dimensions.¹² The electrical conductivity of the flakes is found to be $\sim 10^{-8} \Omega^{-1} \text{ cm}^{-1}$ at 300 °C. The electrical conductivity in the temperature range of 250 – 350 °C follows Arrhenius form with thermal activation energy of 0.87 eV. A deviation from the linear curve is observed above 350 °C and this may arise from the onset of crystallization processes. The electrical conductivity of the titania nanotubes is comparable to other forms of nanostructured titania. The activation energy observed is close to the values reported for nanoporous anatase¹³. At higher temperatures, however, the activation energy and conductivity approach values reported for nanocrystalline anatase¹⁴.

4. SUMMARY

This work presents the fabrication and characterization of highly ordered TiO₂ nanotubes using the electrochemical anodization method. The conductivity of the TiO₂ nanotubes is between those of nanoporous and nanocrystalline anatase. The activation energy for electrical transport in TiO₂ nanotubes over the temperature range 250 - 350 °C was found to be 0.87 eV.

These measurements pave the way for more comprehensive measurements of synthesis/structure/property relationships that are necessary for developing the understanding that is essential for optimal utilization of TiO₂ in energy applications.

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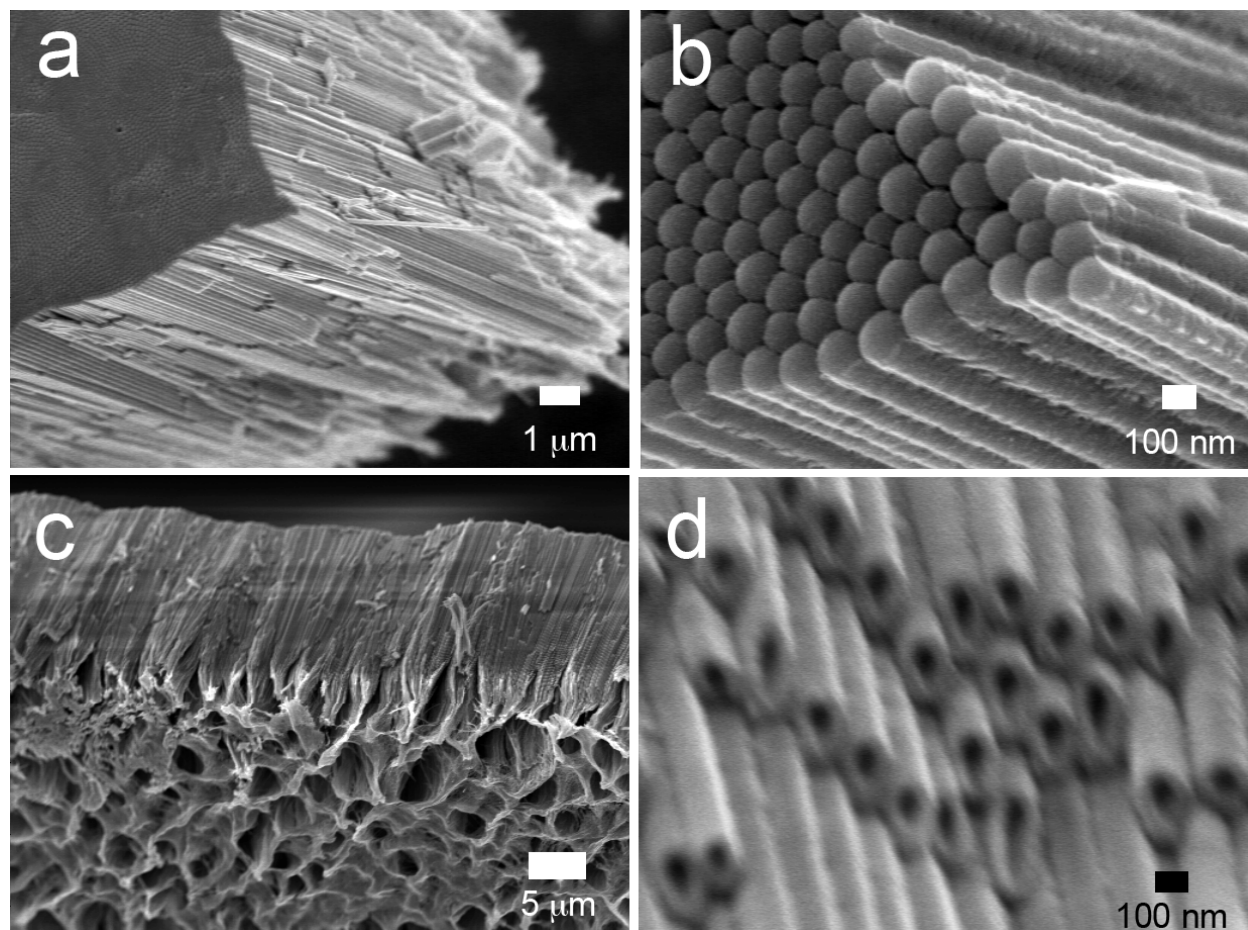
FIGURES

FIG 1: FESEM images of flakes of TiO_2 nanotubes formed on the Ti foil after anodization at 55 VDC for 24 hours. (a, b) "back" surface that was in contact with Ti foil before flake peel-off; (c, d) "front" or external surface. The distortion in (d) is due to charging of the sample during imaging.

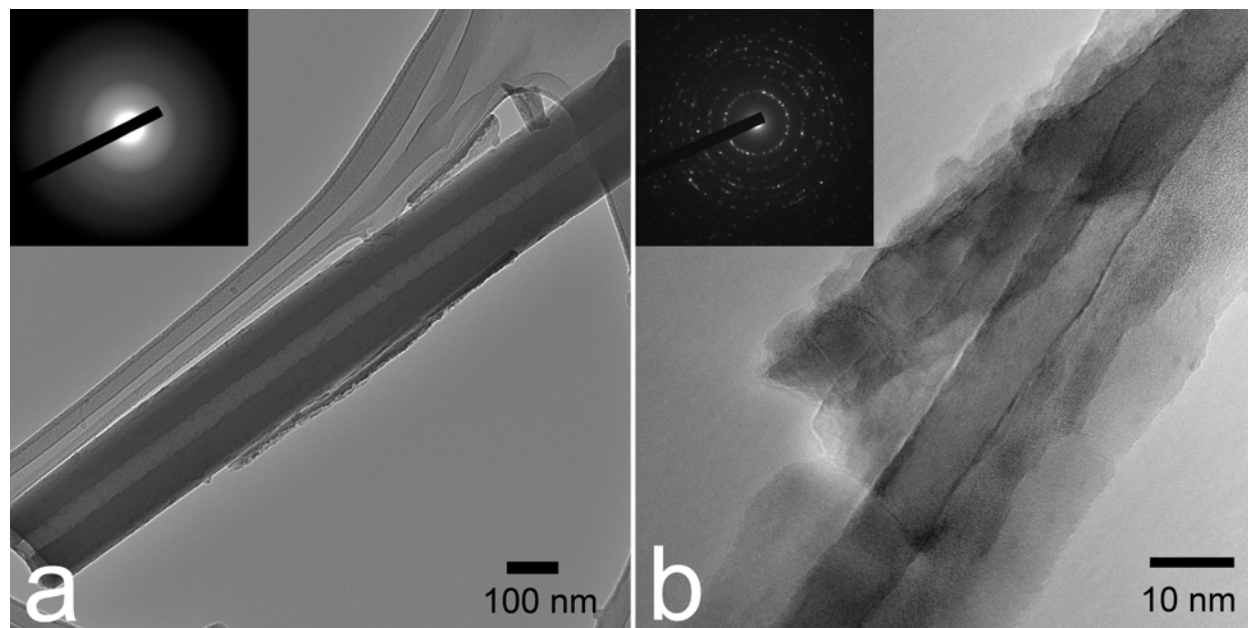


FIG 2: TEM images of TiO_2 nanotube samples: (a) as-prepared, and (b) after 250 °C anneal in air. The insets are the corresponding selected area TEM diffraction patterns.

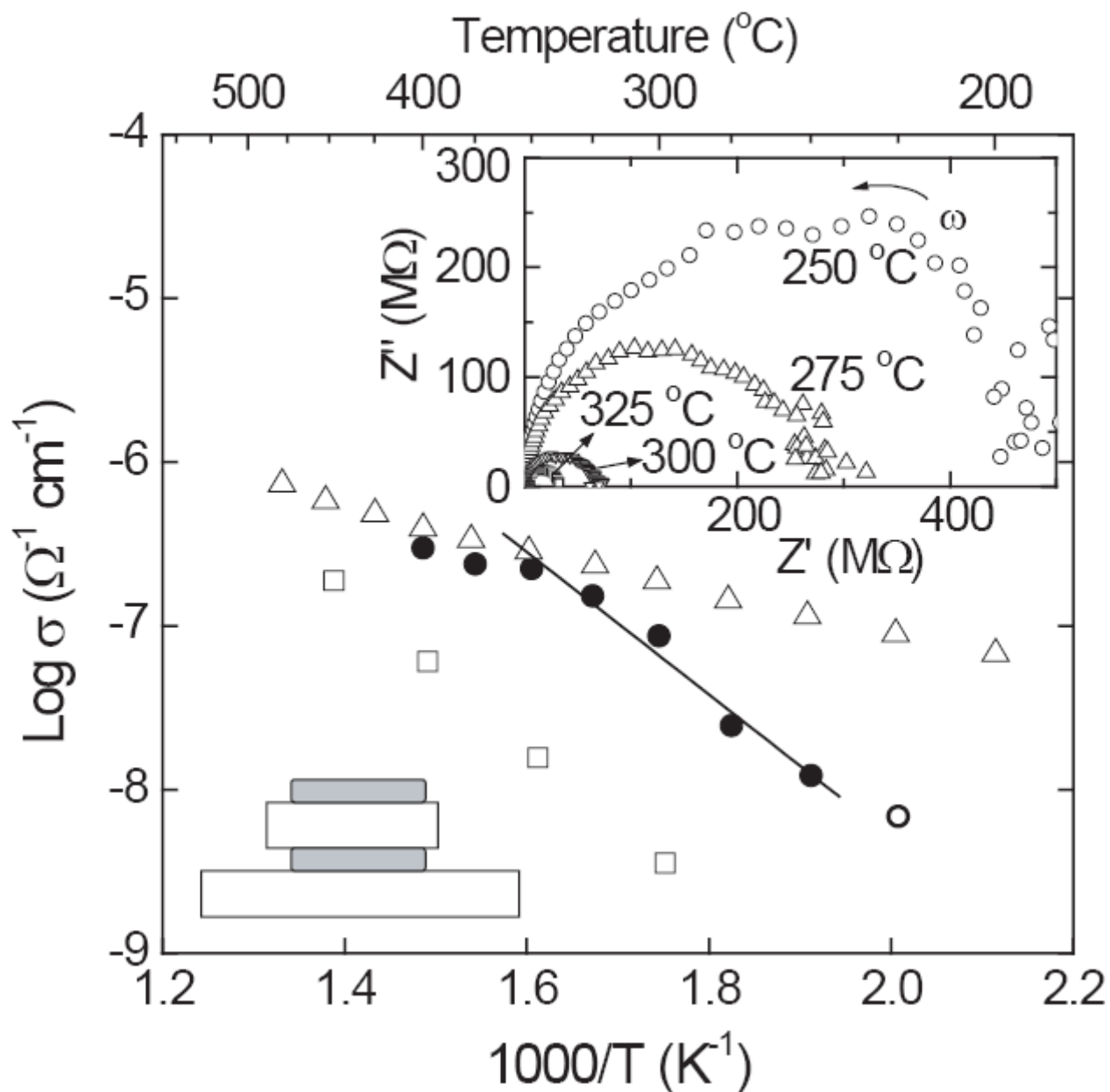


FIG 3: Arrhenius plot of the electrical conductivity of TiO₂ nanotubes (circles) in air, with no prior annealing treatment. Sample measured at 225 °C has a significant amorphous component and is represented by an open circle. The line is fitted to the data from 250 °C through 350 °C. The insets show schematic of measurement geometry and impedance plots at several temperatures. Literature data for nanoporous anatase¹³ (squares) and nanocrystalline anatase¹⁴ (triangles) thin films are shown for comparison.